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Central exclusive scalar luminosities from the linked dipole chain model gluon densities

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Abstract: We investigate the implication of uncertainties in the unintegrated gluon distribution for the predictions for central exclusive production of scalars at hadron colliders. We use parameterizations of the $k_\perp$-unintegrated gluon density obtained from the Linked Dipole Chain model, applying different options for the treatment of non-leading terms. We find that the luminosity function for central exclusive production is very sensitive to details of the transverse momentum distribution of the gluon which, contrary to the $k_\perp$-integrated distribution, is not very well constrained experimentally.

Keywords: QCD, Parton Model, Phenomenological Models, Hadronic Colliders.

Contents

1. Introduction

To detect the Higgs at hadron colliders such as the Tevatron or the LHC is far from a trivial task. Especially if it is rather light and predominantly decays into bottom quarks, the background from standard QCD processes is huge, making the expression "needle in a haystack" seem like a severe understatement. Looking for Higgs signals in the relatively clean environment of diffractive events is therefore an appealing prospect, provided the cross sections are sufficiently high. Several suggestions for what kind of diffractive processes could be used and how to calculate the corresponding cross section for the Higgs and the background have been made [1]–[8].

The cleanest and maybe the most promising process is usually referred to as central exclusive Higgs production, pp$\to$p+H+p (where the + symbolizes a large rapidity gap). It was first suggested in [1, 2] and has lately been developed further by Khoze, Martin and Ryskin (KhMR)[1][5]. This process has several advantages. If the protons are scattered at small angles with small energy loss and they are detected in very forward taggers, the centrally produced system is constrained to be in a scalar state, which reduces the background from e.g. normal QCD production of b-jets. By matching the mass of the central system as measured with the central detectors, with the mass calculated from the energy loss of the scattered protons, it is possible to exclude events with extra radiation outside the reach of the detectors.

There is currently much discussion about which, if any, of the suggested diffractive Higgs processes could be detected at the LHC, and how to reliably calculate them. For a recent review we refer the reader to [10]. In this paper we will only concern ourselves with the model by KhMR and concentrate on one of its weaknesses, namely the uncertainty in their prediction due to the poorly constrained unintegrated gluon densities.

[1] We shall here refer to their calculation as KhMR to distinguish it from the KMR procedure for obtaining unintegrated gluon densities from integrated ones by Kimber, Martin and Ryskin [9].

JHEP02(2004)042

To calculate the central exclusive Higgs cross section, KhMR starts off with the standard gg→H cross section and adds the exchange of an extra gluon to ensure that no net colour is emitted by the protons. Then one must make sure that there is no additional radiation what so ever in the event, which gives rise to so-called soft and hard gap-survival probabilities. The soft survival probability ensures that the protons do not undergo any additional soft rescatterings, while the hard survival probability ensures that the there is no additional radiation from the exchanged gluons. Since the probability to emit really soft gluons diverges, it is necessary to introduce some natural cutoff, in order for the latter survival probability to remain finite. This is accomplished by letting the exchanged gluons have finite transverse momenta so that soft gluons cannot resolve the individual colour flows in the total colour singlet exchange. These transverse momenta must compensate each other so that the net transverse momenta of the scattered protons are zero. This means that the two gluons emitted from each proton are highly correlated and it is necessary to introduce so-called off-diagonal, or skewed, parton densities (odPDFs), which in addition must be $k_\perp$-unintegrated (oduPDFs[2]). With this formalism it is then assumed to be possible to factorize[3] the central exclusive production of any scalar resonance, R, into the standard partonic gg→ R cross section multiplied by a gluon luminosity function which includes both the additional gluon exchange and the gap-survival probabilities. In this way we can turn any hadron collider with forward taggers into a kind of colour-singlet gluon collider with variable center of mass energy.

There are several uncertainties associated with this process. Both theoretical ones, such as how to calculate the soft survival probability, and experimental ones, such as how well the scattered protons can be measured. In this paper we will concentrate on another theoretical uncertainty, namely how well we know the oduPDFs which enters to the fourth power in the cross section. The quoted PDF uncertainty in [5] is a factor of two,[4] which may seem large, but we will here argue that the uncertainty may be even larger.

The factor of two uncertainty was obtained by using a particular procedure to obtain the gluon oduPDF from the standard diagonal integrated gluon PDF, and then using different parameterizations for the latter. The problem with this estimate is that the diagonal integrated gluon PDF is fairly well constrained experimentally, while the diagonal unintegrated one is not, and the off-diagonal unintegrated even less so. In this paper we will use an alternative way to obtain the gluon uPDF, based on the so-called Linked Dipole Chain model [13, 14], which is a reformulation of the CCFM [15, 16] evolution for uPDFs. With the LDC model the uPDFs can in principle be better constrained since it is possible to compare with less inclusive experimental data, looking at details of the hadronic final states of events. Especially observables such as forward jet rates in DIS should be sensitive to the actual $k_\perp$-distribution of gluons in the proton. Unfortunately it turns out to be

[2]Throughout this paper we shall use the following abbreviations: PDF refers to the standard diagonal integrated parton (gluon) density, uPDF is the diagonal $k_\perp$-unintegrated density, odPDF is the off-diagonal integrated and oduPDF is the off-diagonal $k_\perp$-unintegrated density.

[3]There is to our knowledge, however, no formal factorization theorem for off-diagonal, unintegrated parton densities.

[4]In later papers the quoted uncertainty is factor 2.5 up or down [11, 12]

JHEP02(2004)042

extremely difficult to reproduce such observables, even with the LDC. This is why we will here not be able to constrain the prediction for the central exclusive production, but on the contrary conclude that the uncertainties are larger than one might expect.

The outline of this paper is as follows. First we recapitulate in section 2 the main points of the calculation of Khoze, Martin and Ryskin. Then in section 3 we briefly describe the Linked Dipole Chain model and explain how we use it to obtain the central exclusive luminosity function. In section 4 we present our results and compare them with the calculation of Khoze, Martin and Ryskin, leading us to the conclusions presented in section 5.

2. Central exclusive production

The general idea for central exclusive production of a scalar particle such as the Higgs boson[5] is that two gluons with no net quantum number fuse into a Higgs via the standard heavy quark triangle diagram, whereas another semi-hard gluon guarantees that there is no net colour flow between the protons. This is shown in figure 1, where it is also indicated that the exchanged semi-hard gluon should also compensate the transverse momentum $k_\perp$ of the gluons producing the Higgs, so that the protons are scattered with little or no transverse momenta.

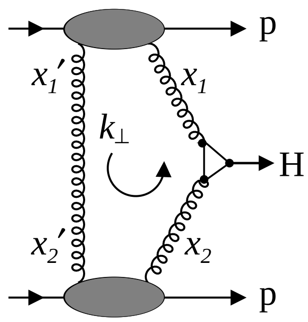

Figure 1: The basic diagram for exclusive production of the Higgs boson

Several types of radiation can destroy the diffractive character of the interaction. An additional gluon or quark which destroys the color singlet can be emitted by one of the gluons. For additional gluons of $q_\perp > k_\perp$ this will be taken care of by a *hard* survival probability given by a Sudakov form factor (see eq. (2.5) below) which guarantees that no gluon or quark with $q_\perp$ between $k_\perp$ and the hard scale given by M is emitted.

In principle there is also a probability of emitting a gluon of transverse momentum squared less then $k_\perp$ and this probability diverges for small $q_\perp$. However, the $k_\perp$ here acts as an effective cut off since a gluon with a wavelength larger than $1/k_\perp$ will not be able to resolve the individual colour flow of the two gluons, but will only see a color singlet being exchanged. The assumption is that the typical $k_\perp$ will be larger than a GeV or two due to the Sudakov suppression, and rather than having a continuous suppression of softer gluons, $k_\perp$ can be used as a sharp cutoff.

Another process which reduces the number of diffractive events is additional soft rescattering of the spectator partons. This is taken care of by a soft survival probability, S^2, the value of which can be be estimated by several different models. Here we will use the same estimates as in [5] where S^2 is taken to be 0.045 for the Tevatron and 0.02 for LHC.

[5]We will in the following talk only about the Higgs, but note that the formalism is valid for the production of any scalar system of particles.

JHEP02(2004)042

Finally we must make sure that the protons remain intact, which gives us a suppression depending on the momentum transfer to each the protons, $t = (p_i - p_f)^2$:

$$P = e^{b(p_i - p_f)^2}\,,$$

which will be integrated over. Assuming that possible shrinkage effects can be neglected it simply gives a suppression factor $1/b^2$, and we will here use the same value as in [5]: $b = 4\ \mathrm{GeV}^{-2}$.

The exclusive cross section of $pp \to ppH$ is then assumesd to factorize into the form

$$\sigma = \int \hat{\sigma}_{gg\to H}(M^2) \frac{\delta^2 \mathcal{L}}{\delta y \delta \ln M^2} dy d\ln M^2\,,$$

where $\hat{\sigma}$ denotes the basic $gg \to H$ cross section and

$$\begin{aligned} L(M,y) &= \frac{\delta^2 \mathcal{L}}{\delta y \delta \ln M^2} \qquad (2.1)\\ &= S^2 \left[\frac{\pi}{(N_c^2-1)b} \int^{M^2/4} \frac{dk_\perp^2}{k_\perp^4} f_g\left(x_1, x_1', k_\perp^2, \frac{M^2}{4}\right) f_g\left(x_2, x_2', k_\perp^2, \frac{M^2}{4}\right)\right]^2 \end{aligned}$$

with $x_{1,2} = e^{\pm y} M/E_{\mathrm{cm}}$, is the luminosity function for producing two gluons attached to the central process at rapidity y and mass M of the Higgs. In principle one should be using an off-shell version of $\hat{\sigma}$ (see eg. [17]) which then would have a $k_\perp$ dependence, hence breaking the factorization, but we shall find below that the main contribution comes from rather small $k_\perp$ and at least for large masses the factorization should hold.

The equation for the luminosity contains the off-diagonal unintegrated gluon densities, $f(x, x', k_\perp^2, \mu^2)$. These should be interpreted as the amplitude related to the probability of finding two gluons in a proton carrying equal but opposite transverse momentum, $k_\perp$, and carrying energy fractions x and x' each, one of which is being probed by a hard scale μ^2. To obtain these density functions in [5] the two step procedure presented in [18] was used. First they obtain the odPDF from the standard gluon PDF, in the here relevant limit of $x' \ll x$:

$$H(x, x', \mu^2) \approx R_g x g(x, \mu^2)\,. \qquad (2.2)$$

The R_g factor depends on the x-behavior of the PDF, so that for $xg(x,\mu^2) \propto x^{-\lambda}$ [19],

$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + 5/2)}{\Gamma(\lambda+4)} \approx 1 + 0.82\lambda + 0.56\lambda^2 + \mathcal{O}(\lambda^3)\,. \qquad (2.3)$$

This factor can be taken approximately constant and we will then use the values quoted in [5]: 1.2 for the LHC and 1.4 at the Tevatron. We note, however, that it could also be taken to depend on both x and μ^2 by using[6] $\lambda = d\ln xg(x,\mu^2)/d\ln(1/x)$.

In the next step it is assumed that the oduPDF can be obtained from the odPDF in the same way as the uPDF can be obtained from the standard PDF. In the latter case one can use the KMR prescription introduced in [9], where

$$G(x, k_\perp^2, \mu^2) \approx \frac{d}{d\ln k_\perp^2}\left[xg(x,k_\perp^2) T(k_\perp^2, \mu^2)\right]\,, \qquad (2.4)$$

[6] Which was actually done in [5] to obtain the luminosities [20].

JHEP02(2004)042

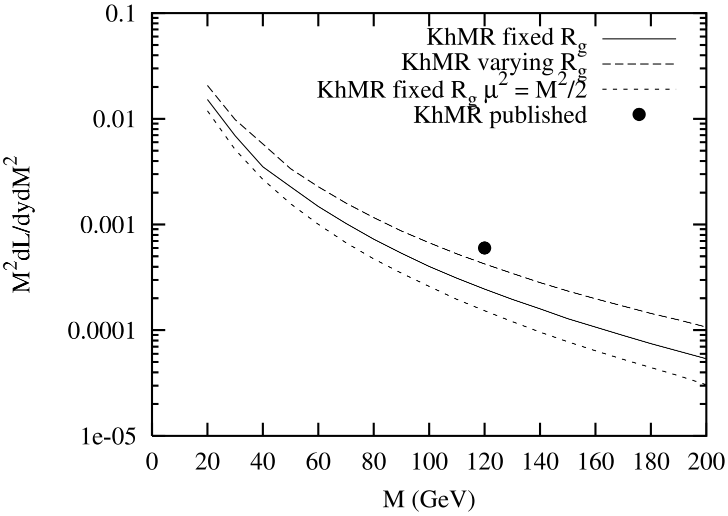

Figure 2: The exclusive luminosity as a function of M for fixed rapidity, $y = 0$, at the LHC, as calculated according to eqs. (2.1) and (2.6) with fixed $R_g = 1.2$ (full line) and with varying R_g according to eq. (2.3) (long-dashed line). The point is the the value quoted in [5]. Short-dashed line is the same as the full line but using the scale $\mu^2 = M^2/2$ rather than $\mu^2 = M^2/4$ in the oduPDFs.

which then corresponds to the probability of finding a gluon in the proton with transverse momentum $k_\perp$ and energy fraction x when probed with a hard scale μ^2. T is here the survival probability of the gluon given by the Sudakov form factor,

$$-\ln T(k_\perp^2, \mu^2) = \int_{k_\perp^2}^{\mu^2} \frac{dq_\perp^2}{q_\perp^2} \frac{\alpha_S(q_\perp^2)}{2\pi} \int_0^{\frac{\mu}{\mu + k_\perp}} dz \left[zP_g(z) + n_f P_q(z) \right]. \tag{2.5}$$

To get the oduPDF one then starts from eq. (2.2) and get by analogy in the limit $x' \ll x$

$$f_g(x, x', k_\perp^2, \mu^2) \approx \frac{d}{d\ln k_\perp^2} \left[R_g x g(x, k_\perp^2) \sqrt{T(k_\perp^2, \mu^2)} \right], \tag{2.6}$$

where the square root of the Sudakov comes about because only one of the two gluons are probed by the hard scale.

In figure 2 we show our calculation of the luminosity function for central rapidity at the LHC using eq. (2.1). We use both a constant $R_g = 1.2$ and a varying one according to eq. (2.3) and we find that the treatment of R_g does make a difference. The latter alternative is closer to the result [5], but it is not exactly the same due to differences in the handling of the α_S in the Sudakov and the lower limit in the integral of eq. (2.1). We use a leading order α_S and the cutoff is taken to be the input scale of the MRST99 (central-g L300-DIS) [21] used as the starting PDF in eq. (2.2).

We note that the scale used in the oduPDFs in [5] is $\mu^2 = M^2/4$ rather than the somewhat more natural one $\mu^2 = M^2$. Although we realize that in a leading order calculation like this the scale choice is somewhat ambiguous. In figure 2 we show that the scale choice in fact makes a rather big difference, the luminosity function is reduced by up to 50% by increasing the scale a factor of two.

JHEP02(2004)042

3. The linked dipole chain model

We will here only describe the main characteristics of the LDC model and instead refer the reader to refs. [13, 14, 22] for a more detailed description. The Linked Dipole Chain model is a reformulation and generalization of the CCFM evolution for the uPDFs. CCFM has the property that it reproduces BFKL evolution [23, 24] for asymptotically large energies (small x) and is also similar to standard DGLAP evolution [25]–[28] for large virtualities and larger x. It does this by carefully considering coherence effects between gluons emitted from the evolution process, allowing only gluons ordered in angle to be emitted in the initial state, and thus contribute to the uPDFs, while non-ordered gluons are treated as final state radiation off the initial state gluons.

The LDC model is based on the observation that the dominant features of the parton chains are determined by a subset of emitted gluons, which is ordered in both light-cone components, q_+ *and* q_-, (which implies that they are also ordered in angle or rapidity y) and with $q_{\perp i}$ satisfying the constraint

$$q_{\perp i} > \min(k_{\perp i}, k_{\perp,i-1})\,, \tag{3.1}$$

where q and k are the momenta of the emitted and propagating gluons respectively as indicated in figure 3. In LDC this subset (called "primary" gluons, or the backbone of the chain) forms the chain of initial state radiation, and all other emissions are treated as final state radiation.

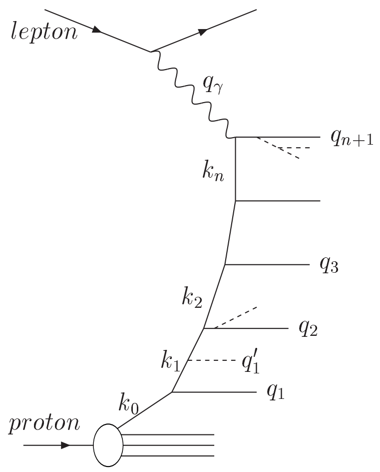

Figure 3: A fan diagram for a DIS event. The quasi-real partons from the initial-state radiation are denoted q_i, and the virtual propagators k_i. The dashed lines denote final-state radiation.

This redefinition of the separation between initial- and final-state implies that one single chain of initial-state emissions in the LDC model corresponds to a whole set of CCFM chains. As was shown in ref. [13], when summing over the contributions from all chains of this set, the resulting equations for the primary chains is greatly simplified. In particular the so-called non-eikonal form factors present in the CCFM splitting functions do not appear explicitly in LDC. The LDC formulation can also be easily made forward-backward symmetric, so that in DIS, the evolution can be equally well formulated from the virtual photon side or from the proton side.

In the small-x limit, keeping only the $1/z$ term of the gluon splitting function we can write the perturbative part of the gluon uPDF as the sum of all possible chains ending up with a gluon at a certain x and $k_\perp^2$

$$\mathcal{G}(x, k_\perp^2) \sim \sum_n \int \prod^n \bar{\alpha}\frac{dz_i}{z_i}\frac{d^2q_{\perp i}}{\pi q_{\perp i}^2}\theta(q_{+,i-1} - q_{+i})\theta(q_{-i} - q_{-,i-1})\delta(x - \Pi z_i)\delta\left(\ln\frac{k_\perp^2}{k_{\perp n}^2}\right), \tag{3.2}$$

where $\overline{\alpha} = 3\alpha_s/\pi$. For finite x it is straight forward to add not only the $1/(1-z)$ to the gluon splitting function, as is also done in CCFM, but also to include the full splitting function with non-singular terms. The $z = 1$ pole then needs to be regularized with a

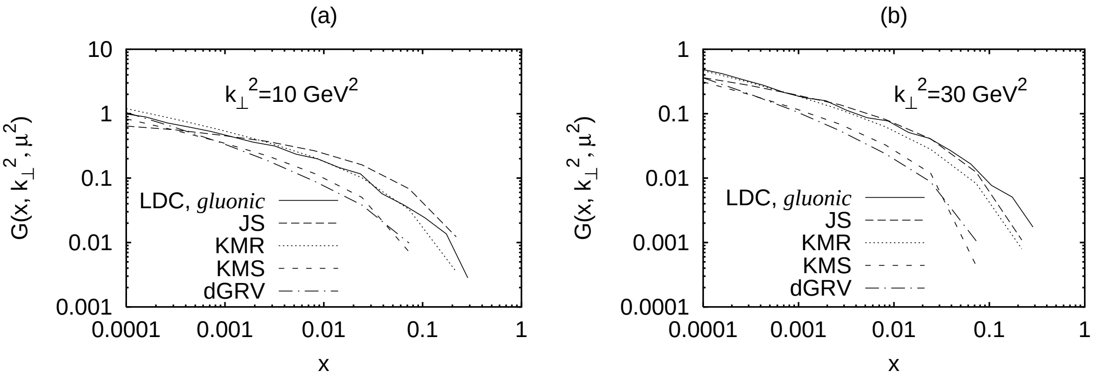

Figure 4: The LDC *gluonic* unintegrated gluon distribution function (full curve), compared to the corresponding results of JS [36] (long-dashed curve), KMR [9] (dotted curve), KMS [37] (short-dashed curve) and a simple derivative of the GRV [38] PDF parameterization (dash-dotted curve) as functions of x for (a) $k_\perp^2 = 10\,\mathrm{GeV}^2$ and (b) $k_\perp^2 = 30\,\mathrm{GeV}^2$. Results for the two-scaled functions, LDC, JS and KMR, with $\mu = 2k_\perp$, are shown together with the 1-scaled distribution functions of KMS and dGRV.

Sudakov form factor Δ_S of the form

$$\ln\Delta_\mathrm{S} = -\int \frac{dq_\perp^2}{q_\perp^2}\frac{\alpha_s}{2\pi} z dz P_\mathrm{gg}(z)\Theta_\mathrm{order}\,, \tag{3.3}$$

where Θ_order limits the integration to the phase space region where initial-state emissions are allowed according to LDC. It is also straight forward to add quarks in the evolution with the appropriate modification of the Sudakov form factors.

The LDC model can easily be implemented in an event generator which is then able to generate complete events in DIS with final state radiation added according to the dipole cascade model [29, 30] and hadronization according to the Lund model [31]. One advantage of having an event generator implementation is that energy and momentum can be conserved in each emission. Since the lack of momentum conservation in the BFKL formalism is the main reason for the huge next-to-leading logarithmic corrections [32], the LDC model is therefore expected to have smaller sub-leading corrections (see [33] for a more detailed discussion on this).

The perturbative form of the uPDF in eq. (3.2) needs to be convoluted with non-perturbative input PDFs, the form of which are fitted to reproduce the experimental data on F_2. This has all been implemented in the LDCMC program [34], and the resulting events can be compared directly to experimental data from eg. HERA. One of the most important observables is the rate of forward jets which is sensitive to parton evolution with unordered tranverse momenta, which is modeled by BFKL, CCFM and LDC, but is not allowed DGLAP. This observable should also be especially sensitive to the actual $k_\perp$distribution of gluons in the proton. It turns out that the forward jet rates can indeed be reproduced by LDCMC (as well as with the CCFM event generator CASCADE [35]) but only if only gluons are included in the evolution and if non-singular terms are excluded from the gluon splitting function [33]. So far there is no satisfactory explanation for this behavior.

JHEP02(2004)042

The LDC gluon uPDF has been extracted by generating a DIS events with LDCMC and measuring the gluon density as described in [22]. The density depends on two scales, $k_\perp$and a scale, $\bar{q}$, related to the maximum angle allowed for the emitted gluons, which is related to the virtuality μ^2 of the hard sub-process. In LDC, similarly to the KMR prescription, the uPDF approximately factorizes into a single scale uPDF and a Sudakov form factor:

$$G(x,k_\perp^2,\mu^2) \approx G(x,k_\perp^2) \times \Delta_S(k_\perp^2,\mu^2)\,. \tag{3.4}$$

This density can then be compared to other approaches and one finds that the results are quite varying as the examples in figure 4 shows. Even looking only at the proper two-scale uPDFs, factors of two difference are not uncommon.

Due to the $k_\perp$-unordered nature of the LDC evolution, the relationship between the uPDF and the standard gluon density is different from eq. (2.4), as the integrated gluon at a scale μ^2 also receives a contribution, although suppressed, from gluons with $k_\perp > \mu$, and in [22] the following expression was obtained:

$$\begin{aligned} xg(x,\mu^2) = {} & G(x,k_{\perp 0}^2)\Delta_S(k_{\perp 0}^2,\mu^2) + \\ & + \int_{k_{\perp 0}^2}^{\mu^2} \frac{dk_\perp^2}{k_\perp^2} G(x,k_\perp^2)\Delta_S(k_\perp^2,\mu^2) + \int_{\mu^2}^{\mu^2/x} \frac{dk_\perp^2}{k_\perp^2} G\left(x\frac{k_\perp^2}{\mu^2},k_\perp^2\right)\frac{\mu^2}{k_\perp^2}\,. \end{aligned} \tag{3.5}$$

To obtain the off-diagonal densities needed for the exclusive luminosity function, we assume that a similar approximation can be made as for the KMR densities, that is, in the limit of very small x'

$$f_g^{\mathrm{LDC}}(x,x',k_\perp^2,\mu^2) \approx R_g(x,k_\perp^2)G(x,k_\perp^2)\sqrt{\Delta_S(k_\perp^2,\mu^2)}\,. \tag{3.6}$$

The square root of the Sudakov form factor is used, since only one of the gluons couples to the produced Higgs at the high scale. We will use both a fixed R_g factor as in section 2 and the one which depends explicitly on the x-dependence of the diagonal PDF taken at the relevant scale. It is currently not quite clear to us how large the uncertainties are in this procedure and we come back to it in a future publication.

The LDC uPDFs are only defined down to a cutoff, $k_{\perp 0}$, below which we will use the non-perturbative input density, g_0, and arrive at the following expression for the exclusive luminosity function:

$$\begin{aligned} L = S^2\Bigg[\frac{\pi}{(N_c^2-1)b}\Bigg(& \frac{1}{k_{\perp 0}^2}R_g(x_1,k_{\perp 0}^2)g_0(x_1,k_{\perp 0}^2)\Delta_S(k_{\perp 0}^2,M^2)R_g(x_2,k_{\perp 0}^2)g_0(x_2,k_{\perp 0}^2) + \\ & + \int_{k_{\perp 0}^2}^{M^2}\frac{dk_\perp^2}{k_\perp^4}R_g(x_1,k_\perp^2)G(x_1,k_\perp^2)\Delta_S(k_\perp^2,M^2)R_g(x_2,k_\perp^2)G(x_2,k_\perp^2)\Bigg)\Bigg]^2\,. \end{aligned} \tag{3.7}$$

Comparing with eq. (2.1) we note that, besides the different form of the oduPDFs, the scale and the integration limit is taken to be M^2 rather than $M^2/4$. The exact value of the integration limit is not very important, but the scale in the Sudakov form factor is. In fact, the form of the Sudakov form factor is also different. We use

$$\ln\Delta_S(k_\perp^2,M^2) = -\int_{k_\perp^2}^{M^2}\frac{dk_\perp^2}{k_\perp^2}\frac{\alpha_s}{2\pi}\int_0^{1-k_\perp/M} dz\left[zP_g(z) + \sum_q P_q(z)\right], \tag{3.8}$$

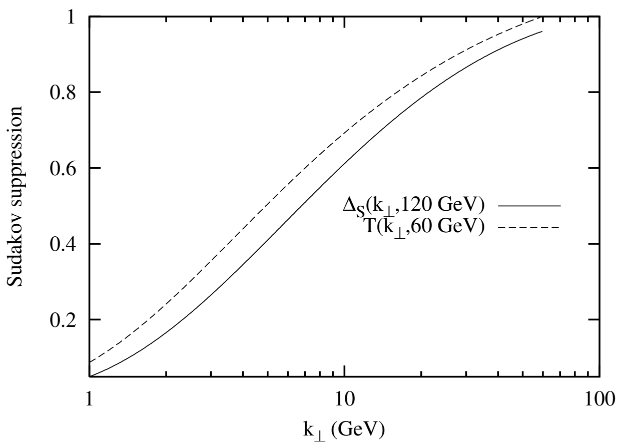

Figure 5: The Sudakov form factor used in the LDC calculation (full line, eq. (3.8)) compared to the one used by KhMR (dashed line, eq. (2.5))

which corresponds to the actual no-emission probability in the phase space region up to the rapidity of the produced Higgs from the incoming gluon. The different integration region in eq. (2.5) as well as the different scale used means that the Sudakov suppression in that case is weaker as shown in figure 5. The difference is not very large, but since the factor comes in squared in the luminosity function for $k_\perp$ of a couple of GeV the difference can easily become larger than a factor two.

One of the main differences between the LDC uPDFs and the KMR ones is that the evolution of former includes emissions with transverse momenta which may be larger than the $k_\perp$ for the probed gluon. This is, of course, kinematically allowed but should be rather suppressed. In any case, it is not clear how to handle such emissions when calculating the off-diagonal densities in eq. (3.6). To investigate the effects of such $k_\perp$-non-ordering we shall below also use as comparison an alternative LDC uPDF where the transverse momentum in the evolution has been limited to be below $k_\perp$.

4. Results

In the following we shall present calculations for the exclusive luminosity using three different parameterizations of the LDC uPDF. The three options differs in the way they treat non-leading effects in the evolution and will be referred to as *standard*, *gluonic* and *leading* as described in [22]:

- *standard* is obtained with the full LDC evolution including the full splitting functions for both gluons and quarks. This option does not describe forward jets very well, but it gives an excellent description of F_2 data.

- *gluonic* is obtained by using only gluons in the LDC evolution, but with the full splitting function. This option does not describe F_2 data as well, especially not at large x, but it agrees better with standard parameterizations of the integrated gluon PDF.

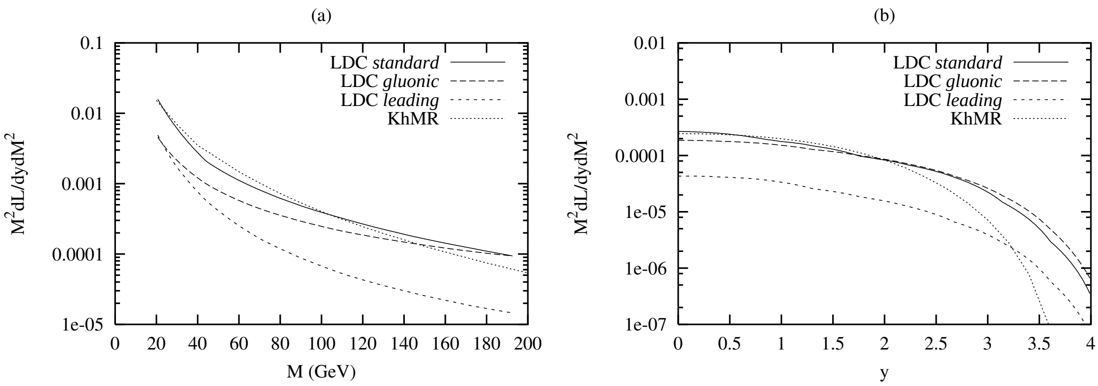

Figure 6: The exclusive luminosity as a function of M for fixed rapidity, $y = 0$ (a) and as a function of rapidity for fixed mass $M = 120\,\text{GeV}$, at the LHC, as calculated according to eq. (3.7). Full line is *standard*, long-dashed line is *gluonic* and short dashed line is *leading*. As comparison the calculation based on KhMR is shown with a dotted line.

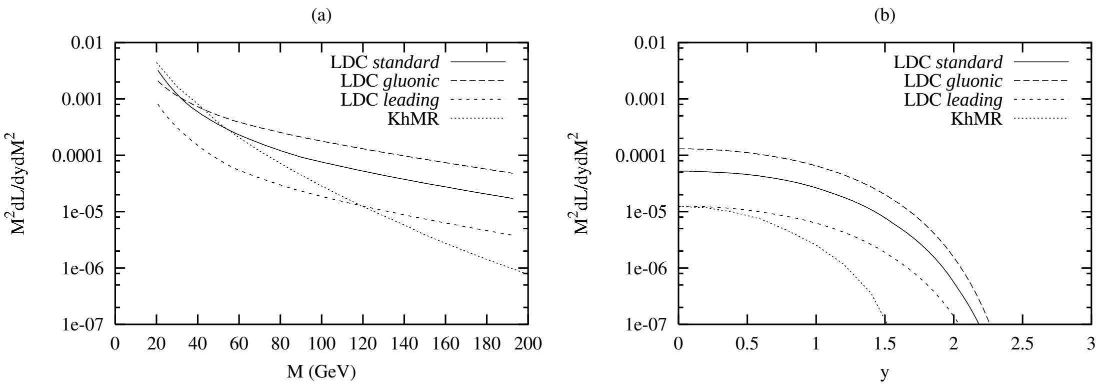

Figure 7: The exclusive luminosity as a function of M for fixed rapidity, $y = 0$ (a) and as a function of rapidity for fixed mass $M = 120\,\text{GeV}$, at the Tevatron, as calculated according to eq. (3.7). The lines are the same as in figure 6.

- *leading* is obtained by using only gluons in the LDC evolution and only the singular terms of the gluon splitting function. Among the three it is the one which describes inclusive data the worst, on the other hand it is the only one which is able to describe the large rate of forward jets measured at HERA.

Clearly, none of these options are in perfect agreement with data, but we will use them here as a parameterization of our ignorance when it comes to unintegrated gluon densities.

In figure 6 and 7 we present our calculations of the luminosity function for the LHC and Tevatron respectively, using eq. (3.7) (with fixed $R_g = 1.2$ and 1.4 respectively). We find that the three options for the LDC evolution give very different results. At the LHC the *standard* is fairly close to the results obtained with the KhMR calculation, while the result for *leading* is up to a factor ten below. We note that for large rapidities in figure 6b the differences between LDC and KhMR is larger also in shape, but this is close to the phase space limit, where one of the gluons carry a large fraction of the proton momentum

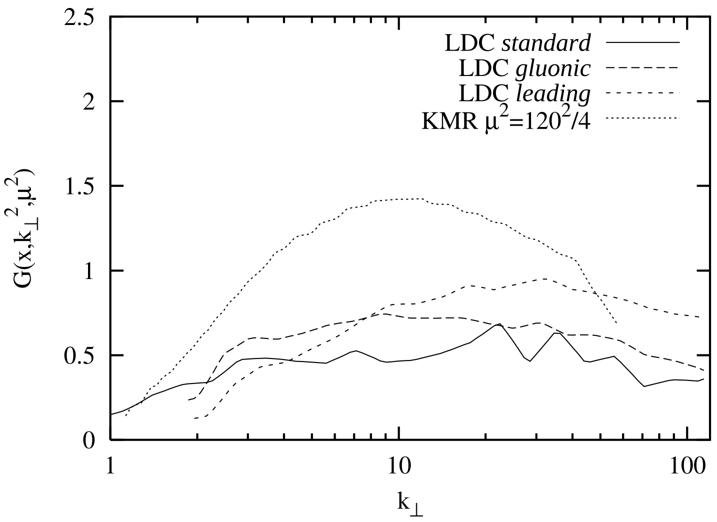

Figure 8: The LDC unintegrated gluon density as a function of $k_\perp$ for $\mu^2 = (120\ GeV)^2$ and $x = 120/14000$ (relevant for the luminosity function in eq. (3.7) for $M = 120$ GeV and $y = 0$). For comparison the KMR uPDF is shown for the same x but for $\mu^2 = (120/2\ GeV)^2$ (relevant for eq. (2.1)). The lines are the same as in figure 6..

and in this region the LDC parameterizations are less well constrained. The same effect is visible at the Tevatron in figure 7 where again the energy fractions are larger, especially for high masses.

The large difference between the three LDC options may seem surprising, especially since the standard integrated gluon PDF is generally higher for *leading* than for the other two. The explanation can be found by studying the $k_\perp$-dependence of the uPDF presented in figure 8. Here we see that *leading* has a harder $k_\perp$ spectrum than the the other two options and that all LDC densities have a flatter spectrum than the KMR one (which is shown at a lower scale corresponding to the one used in the luminosity function). This should be expected since the *leading* also produces more forward jets (in agreement with what is observed experimentally) and hence should give larger $k_\perp$-fluctuations. It turns out that the luminosity function is mostly sensitive to the uPDFs at $k_\perp$-values of around $2-3$ GeV, since smaller and larger values are suppressed by the Sudakov form factor and the $1/k_\perp^4$ factor respectively. Even if the differences in this region is not very large, the uPDF enters to the power four in the luminosity function, thus enhancing the differences (the difference between LDC and KMR is diminished since the square root of the Sudakov formfactor affect the LDC more than the KMR).

To investigate the uncertainties involved in going from the LDC uPDFs to the oduPDFs in eq. (3.6) we show in figure 9 the difference between using a fixed R_g factor and a varying one according to eq. (2.3) [7] with $\lambda = d\ln G(x, k_\perp^2)/d\ln(1/x)$. Comparing with figure 2, we find that the differences are of the same order. We also show the effects of using an

[7]The line is here a bit jagged due to the limited statistics in the Monte Carlo extraction of the LDC uPDF.

(a)

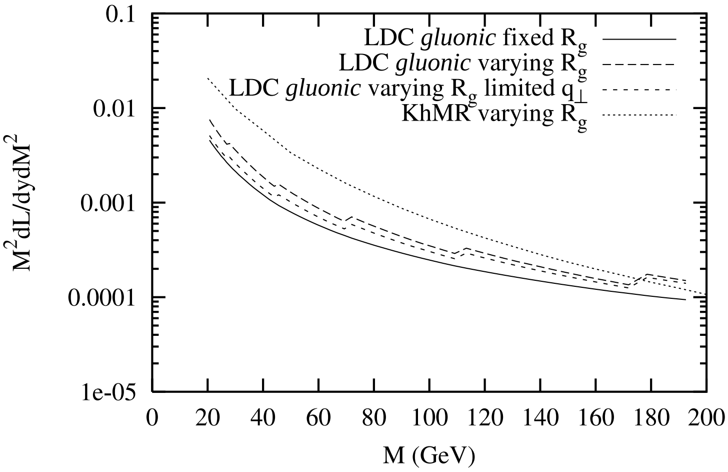

Figure 9: The exclusive luminosity as a function of M for fixed rapidity, $y = 0$ at the LHC, as calculated according to eq. (3.7) using the *gluonic* uPDF of LDC. Full line is with a fixed $R_g = 1.2$, long-dashed and short-dashed lines are with varying R_g but the latter uses a modified version of *gluonic* where the transverse momentum in the evolution has been limited. As comparison the calculation based on KhMR with a varying R_g is shown with a dotted line.

alternative version of the *gluonic* density where the transverse momentum in the evolution has been limited to be below $k_\perp$. This will not only reduce the uPDF somewhat, but it will also slow down the x-evolution, giving a smaller λ and hence a smaller R_g. As expected this effect is quite small, but still noticeable especially at small masses (small x).

5. Conclusions

The partonic evolution at small x is one of the least understood aspects of QCD. Although inclusive Higgs production is not a small-x process and therefore well understood in terms of collinear factorization with well constrained integrated gluon distributions, the exclusive production considered here relies on the exchange of a small-x gluon and is very sensitive to the $k_\perp$ distribution in the less constrained unintegrated gluon distributions.

In this report we have described how we calculate the exclusive luminosity function using the unintegrated gluon distributions obtained within the LDC model, and we have found that different options give widely different results. In particular we note that the option which gives the best description of forward jet production at HERA, which should be sensitive to the actual $k_\perp$-dependence of the gluon in the proton, gives a result which is a factor ten smaller than what was reported by Khoze, Martin and Ryskin in [5]. This option is in theory a worse approximation than the other two and is similar to the double-log approximation discussed by the same authors in [39], which was also shown to give a much smaller result. Contrary to them, however, we do not dismiss the *leading* approximation, as experiments indicate that it better describes the actual $k_\perp$distrubution of the gluon.

There are several uncertainties in our calculations. The relation between the unintegrated gluon and the corresponding off-diagonal unintegrated gluon density not formally derived, but just assumed to be valid by analogy. The results are sensitive to the treatment of the R_g factor and the treatment of the $k_\perp$-unordered nature of LDC evolution. The different options used for the LDC unintegrated densities are in good agreement with different kinds of experimental observables, but none of them agrees with all important observables. It should also be noted that these densities were obtained through a fit to F_2 data only, which is mainly concentrated at small scales. At large scales which are important for reasonable values of the Higgs mass ($\gtrsim$ 120 GeV) the densities are less constrained.

The conclusion of this paper is therefore not that the previous calculations by Khoze, Martin and Ryskin is wrong in any way, but rather that they may have underestimated the uncertainties due to the unintegrated gluon density. We will not go so far as to say that the uncertainties are as large as a factor ten, but we believe that they are much larger than a factor of two. This does not mean that the prospects of using tagged forward protons to try to find the Higgs or other scalar particles at the LHC becomes less interesting, but our current understanding of the small-x sector of QCD clearly needs to be improved before we can give reliable predictions for such processes.

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